# Ocean Surface Temperature Response to Atmosphere-Ocean Interaction of the MJO
## *A component of Coupled Air-Wave-Sea Processes in the Subtropics Departmental Research Initiative*

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## LONG-TERM GOALS

We are part of a multi-institutional research team funded by the ONR-sponsored the ***Coupled Air-Wave-Sea Processes in the Subtropics Departmental Research Initiative***. The primary research goals of the program include: (i) Surface flux observations in regions of known coupled modes, (ii) Co-located observations of atmospheric and oceanic vertical structure and evolution, and (iii) Ocean mixed layer and marine atmospheric boundary layer dynamics, and interactions between these and the surface wave field, the free atmosphere, and the interior ocean. Our goals are to contribute innovative measurements, analyses and models of the sea surface temperature at length scales as small as a 1 meter up to 100's of kilometers. This characterization includes the skin SST, waves, wave breaking, and upper ocean processes.

## OBJECTIVES

The Madden-Julian Oscillation (MJO) is an intraseasonal oscillation which is most closely identified with the tropical Indian and Pacific Oceans, characterized by an eastward progression of a large (~2000 km) pattern, extending from the equator into the adjacent subtropical belts, with enhanced and suppressed rainfall. In the context of this DRI, understanding the complex processes involved in locations such as the MJO as it passes over the eastern Indian Ocean are necessary steps for evaluating the modulation of SST and atmosphere-ocean feedbacks, for validating ocean and climate models, and for making prognostic assessments of oceanic circulation.

A recent MJO workshop [*Sperber and Waliser*, 2008] has suggested that observations are lacking for many important processes (e.g. convective momentum transport, moistening of the boundary layer, diurnal cycle of shallow convection, and surface fluxes). It also suggests the measurements are needed to provide insight into a variety of MJO characteristics including the transition to and from the convective phase including scale interactions with mesoscale systems, and the diurnal cycle over the land and ocean. The workshop highlighted that a better understanding of the vertical structure of the atmosphere, including clouds, moisture cycling, and related properties (e.g., long wave and shortwave radiation, humidity), is not adequately represented in simulations of the MJO.

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The broad science questions to be addressed by our program include the following:

- How do atmospheric boundary layer processes and sea-air coupling over the eastern Indian Ocean modulate the intensity and spatial extent of MJO and of higher frequency fluctuations?
- What regulates the sea-wave-air interactions and the response of the mixed layer during periods of MJO forcing?
- How do the near-surface profile characteristics evolve over the course of an MJO cycle and at higher frequency fluctuations?

Understanding the complex processes involved in locations such as the MJO as it passes over the eastern Indian Ocean are necessary steps for evaluating the modulation of SST and atmosphere-ocean feedbacks, for validating ocean and climate models, and for making prognostic assessments of oceanic circulation. Our science goals are directly related to the special focus areas of the DRI described above in Long-Term Goals.

Our science goals complement and parallel those of J. Moum of Oregon State. They plan to deploy a fully instrumented Chameleon turbulence profiler along with a bow-mounted CT chain to understand the upper ocean processes important to the MJO cycle from the R/V Revelle. Our science goals also complement and parallel those of J. Edson of the University of Connecticut who plans to make direct measurements of latent heat flux on the R/V Revelle, as well as more conventional rawinsonde launches in addition to turbulent air-sea fluxes from the ship during the IOP. Further, we expect to have interactions with the many PIs aboard the NOAA P-3 aircraft including Shuyi Chen and Qing Wang.

**APPROACH**

Lamont-Doherty Earth Observatory of Columbia University (LDEO) developed an airborne imaging system that utilizes both infrared and visible cameras to map the ocean surface SST and ocean surface processes. We build substantially on our accumulated expertise in sea surface processes and air-sea interaction. We are working within the larger team measuring and characterizing the ocean surface properties, namely SST. Airborne IR imagery will provide high spatial resolution calibrated SST variability. The image scale will be roughly 500 m to 1000 m (depending on altitude) with resolution of order 1 m. This team is contributing the following components to the primary sea surface imagery data gathering effort in LASP/DYNAMO:

- <u>fast response, infrared (IR) imagery</u> to characterize SST signatures including upper-ocean convection, freshwater lenses due to rain, Langmuir circulation, internal waves, ramping of near-surface stratification, etc. at scales of *O*(1m-1000m)
- <u>high resolution video imagery</u> to record general ocean surface conditions and whitecap data using wide field-of-view to quantify scales of *O*(1m-1000m)

With our added payload capacity on the NOAA P-3, thermal infrared (IR) imagery demonstrates the ocean surface processes that are relevant to atmosphere-ocean interaction. As the focus of the measurement module, we will implement a small sensitive uncooled IR camera to map the temperature structure of the ocean's surface. The FLIR SC655 is an un-cooled microbolometer focal plane array of

640 x 480 elements that are sensitive to 8.0-12.0 micron radiation. The microbolometer array performance will allow for the determination of temperature variability of less than 50 mK. Additionally, we will deploy a JADE LWIR 570 Sterling-cooled Mercury-Cadmium-Telluride (MCT) focal plane array of 320 x 240 elements that are sensitive to 8.0-9.3 micron radiation. The MCT focal plane array performance will allow for the determination of temperature variability of less than 20 mK. The combination of cameras will allow us to capture a multitude of scales from $O$(1m - 1000m). Finally, an Imperx model Bobcat 2520 visible camera with 2500 x 2000 elements was deployed for high-resolution determination of the ocean surface structure.

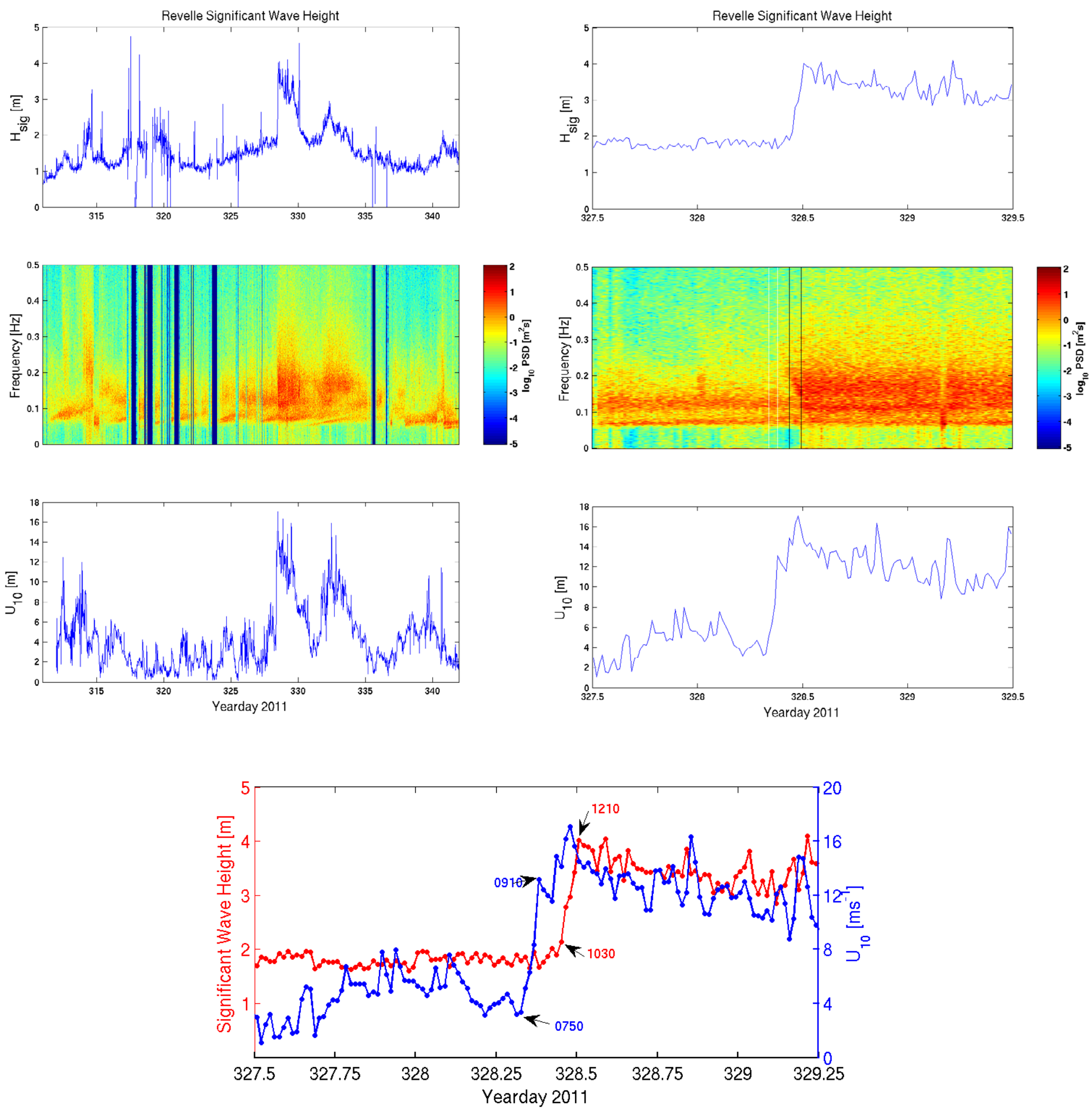



***Figure 1. (TOP LEFT) Significant wave height, wave height spectrogram and wind speed time series for Leg 3 on the R/V Revelle during LASP/DYNAMO. (TOP RIGHT) Zoom into 24 November convection event. (BOTTOM) Significant wave height and wind speed on 24 November convection event.***

We flew on the NOAA P3 aircraft and have worked with Djamal Khelif of UC Irvine and Qing Wang of the Naval Postgraduate School to instrument the manned aircraft. The suite of instruments aboard the NOAA P3 allows us to characterize the surface and atmospheric state, measure net radiative fluxes, and estimate the heat, moisture, and momentum fluxes. These data are used to relate the basic state variables of the atmosphere to remotely-sensed characteristics of the waves and $SST_{skin}$ at the air-sea interface. The main goal of flights with this instrument suite is to characterize the properties of the surface associated with time varying atmospheric conditions of the MJO, including $SST_{skin}$, as well as wave height and fine-scale surface height variation and roughness from laser profiles. A second goal of the manned aircraft P3 mapping is to provide surface information at higher spatial resolution and with better temporal sampling than is available from the satellite data.

The IR and Visible imaging provide an important characterization of the wind-wave field since they are used to characterize the kinematics of wave breaking (white capping only). Analyses of the airborne IR and Visible imagery benefit significantly from flights over the Revelle and/or the mooring array. These provide for a better understanding of the wave effects on the upper ocean turbulence and stratification structure and the wave effects on the air-sea fluxes. These measurements elucidate a variety of mechanisms related to atmospheric and sub-surface phenomena that produce horizontal variability in SST over a wide range of scales under MJO forcing. This study investigates the mesoscale, sub-mesoscale, and small-scale variability.

We also deployed and up- and down-looking radiometer system to measure $SST_{skin}$ aboard the R/V Revelle. The system includes two longwave narrow FOV Heitronics KT-15.82 TIR radiometer (8-14 microns for lower noise levels) instruments that are calibrated to better than 0.05ºC. The upward-looking instrumentation will be used to discriminate real from apparent ice surface temperature variability. Apparent temperature variability in the infrared imagery may arise on partly cloudy days when both the radiatively-cold sky and radiatively-warm clouds reflect into the imager FOV. The overall system accuracy is ±0.05ºC and can sense radiometric temperatures down to –80ºC depending on the integration setting.

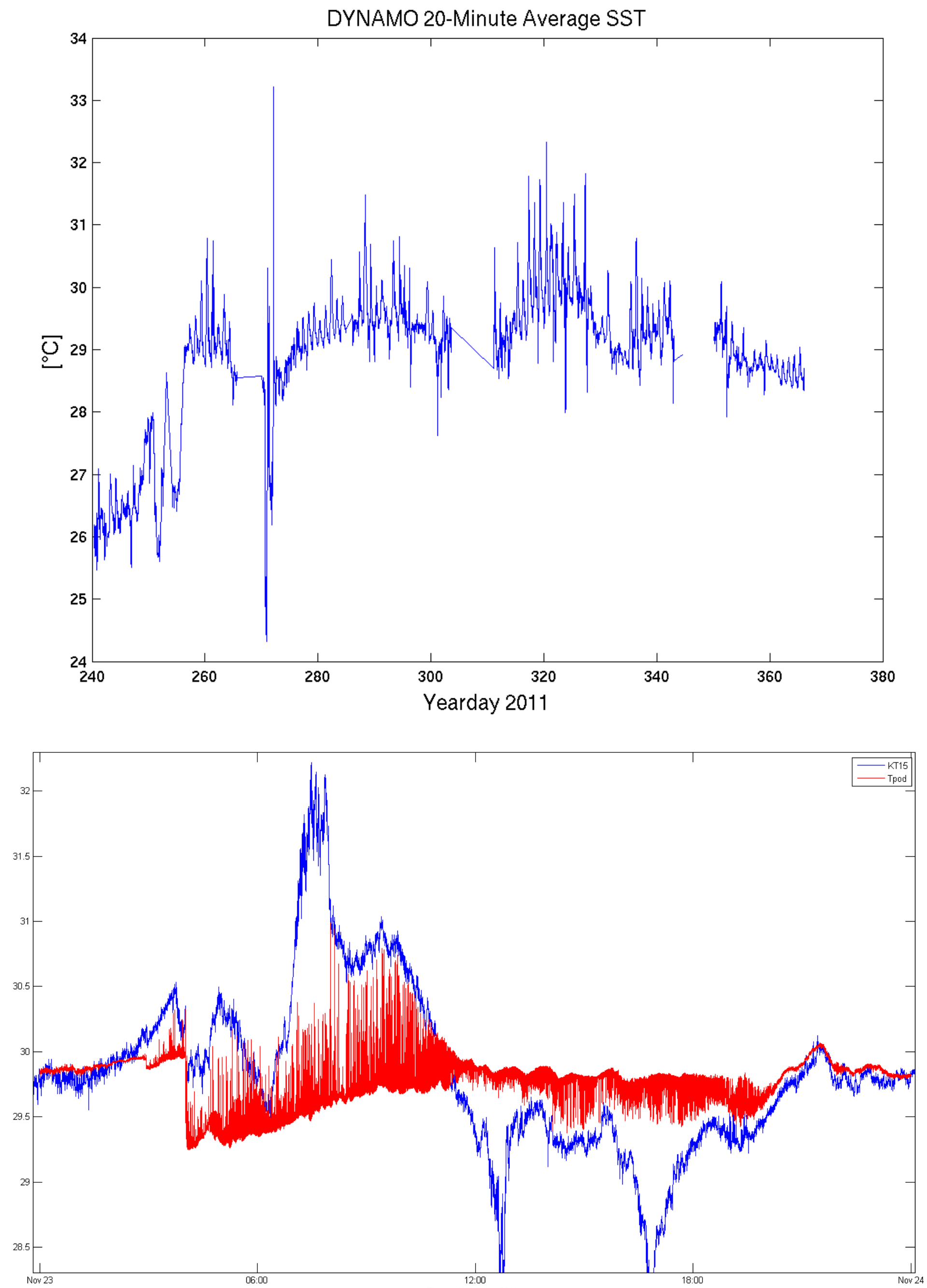



***Figure 2. (TOP) Time series of $SST_{skin}$ measured from the R/V Revelle for the $2^{nd}$, $3^{rd}$ and $4^{th}$ legs. (BOTTOM) Time series of $SST_{skin}$ and $T_{bulk}$ measured from the R/V Revelle on 23 November, 2011.***

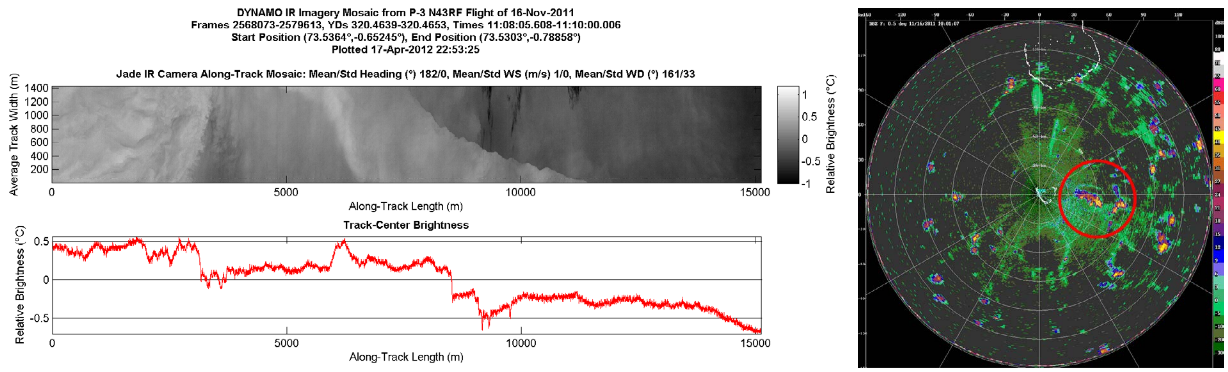



***Figure 3. (LEFT) Mosaic and spatial series of $SST_{skin}$ measured from the NOAA P-3 near Gan Island. (RIGHT) Radar map from Gan Island showing convective event within the red circle. Note the large region of cold cool freshwater in the mosaic of $SST_{skin}$.***

We also measured the waves with a single downward-looking Riegl model LD90-3100VHS laser altimeter boomed out from the jackstaff of the R/V Revelle. The Riegl output was heave compensated using the MotionPak from the direct covariance system also on the jackstaff.

## WORK COMPLETED

In FY12, Lamont-Doherty Earth Observatory of Columbia University (LDEO) participated in the measurement IOP for the P-3 that took place from 3 November 2011 through 15 December 2011 based in Diego Garcia. The overall objectives of the NOAA WP-3D (P-3) field campaign in LASP/DYNAMO are to address the basic science questions/hypotheses regarding air-sea interaction and tropical convection with its unique standalone suite of measurements, and to bridge observations from fixed locations on ships and islands. Measurements from the NOAA P-3 include flight level state and thermodynamics variables, turbulence and high rate temperature and water vapor perturbations, cloud microphysics, atmospheric radiation, surface IR/Visible imaging of SST and waves, and convective activities from the vertical-scanning Doppler radar and the fuselage horizontally scanning radar. Measurements from the NOAA P-3 also include air expendables such as GPS wind-finding dropsondes, Airborne eXpendable Bathy Thermographs (AXBT) and Airborne eXpendable Conductivity Temperature and Depth probes (AXCTD) for atmospheric and oceanic profiling.

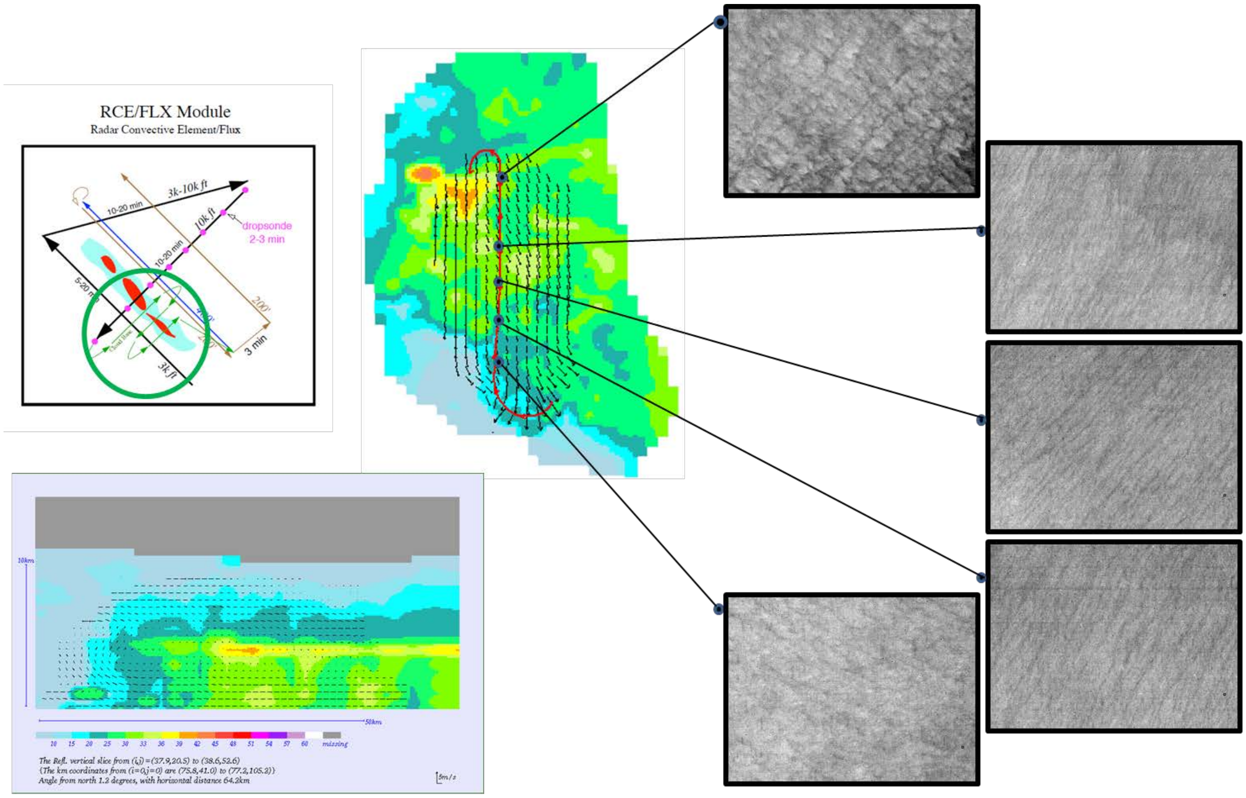



***Figure 4. (UPPER LEFT) RCE/FLX Module schematic. (RIGHT) IR images of the ocean surface during a convective event. (TOP CENTER) Radar image in plan view showing convective gust front and flight track with wind vectors. (BOTTOM LEFT) Radar image in side view of the convective gust front and the vertical structure of the velocity vectors.***

The P-3 science team arrived at Diego Garcia on Nov 3 followed by the arrival of the NOAA P-3 and its crew on Nov. 9. We conduct a total of 12 flights between Nov 11 and Dec 13, 2011 with 10 science focused flights with average duration of about 10 hours, an initial test flight of about 3.5 hours, and the final flight of 4-hour duration for instrument calibration and inter-comparison. The remaining of the P-3 science team and the NOAA crew exited Diego Garcia on Dec 14, which marked the conclusion of the LASP/DYNAMO P-3 field campaign. Combined, P-3 LASP/DYNAMO flights over the Indian Ocean totalled about 104.5 hours out of the total 105 science hours.

We have presented our results at the AMS 30th Conference on Hurricanes and Tropical Meteorology in Ponte Vedra Beach, FL, USA in April 2012, at the AMS 18$^{th}$ Conference on Air-Sea Interaction and 20th Symposium on Boundary-Layers and Turbulence in Boston, MA, USA on 9-13 July 2012 and at the International Geoscience and Remote Sensing Symposium in Munich, Germany in July 2012. We also participated in the ONR LASP / DYNAMO DRI Meeting at the Hilton Back Bay in Boston, MA, USA in July 2012.

## RESULTS

*R/V Revelle Measurements*

Wave height observations from the Riegl on the bow of the R/V Revelle show a strong swell and wind sea throughout most of the 3rd leg (see Full Spectrogram Figure 1 Top Left). Focusing in on the 24 November event (see Zoomed Spectrogram Figure 1 Top Right), we observe these similar sea and swell systems in the Riegl data and are observed at the same frequencies as the WaMoS observes. On 24 November, the wind speed kicked up around 0800 and by 0900 it had reached 13 m $s^{-1}$ (see Wind and SWH Time Series Figure 1 Bottom). The significant wave height (SWH) lagged the wind speed by roughly 2 to 3 hours. Closer inspection of the spectrogram shows that when the wind speed reached the 13 m $s^{-1}$ level at 0900, there is significant energy in a 2$^{nd}$ wind sea system at roughly 0.3 Hz or 3-s period. These are very young seas observed in the Riegl ($C_p$ / $U_{10}$ = 0.5). As 1030 approaches, this wind sea system has downshifted and broadens as it continues to grow until about noon when this 2nd wind sea system has evolved into a broad energetic wind sea that consumes the original sea. This new wind sea is still young compared to the original sea ($C_p$ / $U_{10}$ = 0.8) and is much broader.

$SST_{skin}$ measurements from the KT-15 system aboard the R/V Revelle during the 2$^{nd}$, 3$^{rd}$, and 4$^{th}$ legs are shown in Figure 2 TOP. $SST_{skin}$ shows a strong diurnal signal typically of O(1°C) and is also nominally a cool skin layer for most of the nighttime as well as daytime when the insolation is not overly strong. At times, a warm skin layer can develop. Figure 2 BOTTOM focuses in on a 24-hour period that shows the $SST_{skin}$ as well as the $T_{bulk}$ at 10cm. The $T_{bulk}$ sensor moves up and down with the waves and acts as a profiler near the surface. During times when a cool skin layer exists, the $T_{bulk}$ shows downward spikes that envelope the $SST_{skin}$. During times when a warm skin layer exists, the $T_{bulk}$ shows upward spikes that envelope the $SST_{skin}$. This is some of the first direct evidence that a warm skin layer can exist since the upward spikes never break through the $SST_{skin}$ envelope.

*NOAA P-3 Measurements*

During the suppressed phase of the MJO, Figure 3 (LEFT) shows a mosaic and spatial series of $SST_{skin}$ measured from the LDEO infrared camera along the flight track of the NOAA P-3 during our flights near Gan Island on 16 November. The vertical axis in the mosaic is the cross-track scale and the horizontal axis is the along-track. The flight was at 3680 m altitude, so the cross-track scale was roughly 1.4 km and this flight leg lasted roughly 15 km. Figure 3 (RIGHT) shows a radar map from Gan Island showing convective event that immediately preceded the overflight. Note the large region of cold cool freshwater in the mosaic of $SST_{skin}$. A strong gradient in convection existed between ITCZ and Equator. Weak winds were prevalent and it was dry near Gan. The convective event generated a significant cold pool possibly related to the gust front located in Figure 3 (RIGHT). Note two specific features that appear as a pool of cool water and a sharp frontal feature from warm to colder water. Note that the flight track is due South. The pool of cool water begins at roughly 3 km and ends around 6.5 km. The sharp front occurs around 8.5 km. Both of these features may be due to recent rain from the convective cells in the region as seen in the S-Pol. The robust large-scale temperature gradient of nearly 1°C is real with window and atmosphere effects having been removed. Small-scale temperature variability of 0.1°C $m^{-1}$ with muted and smoothed horizontal scales. Large-scale temperature fronts associated with fresh convective event of 0.5°C.

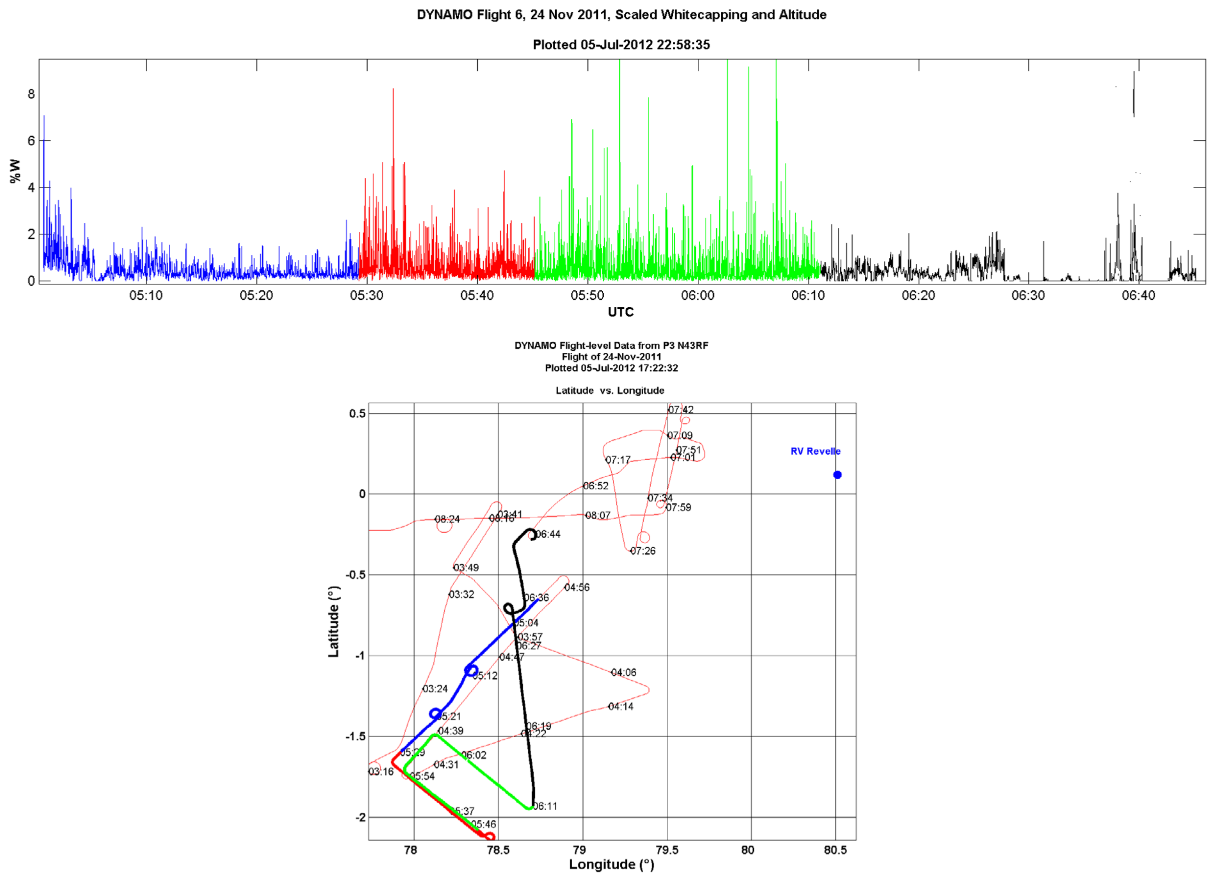
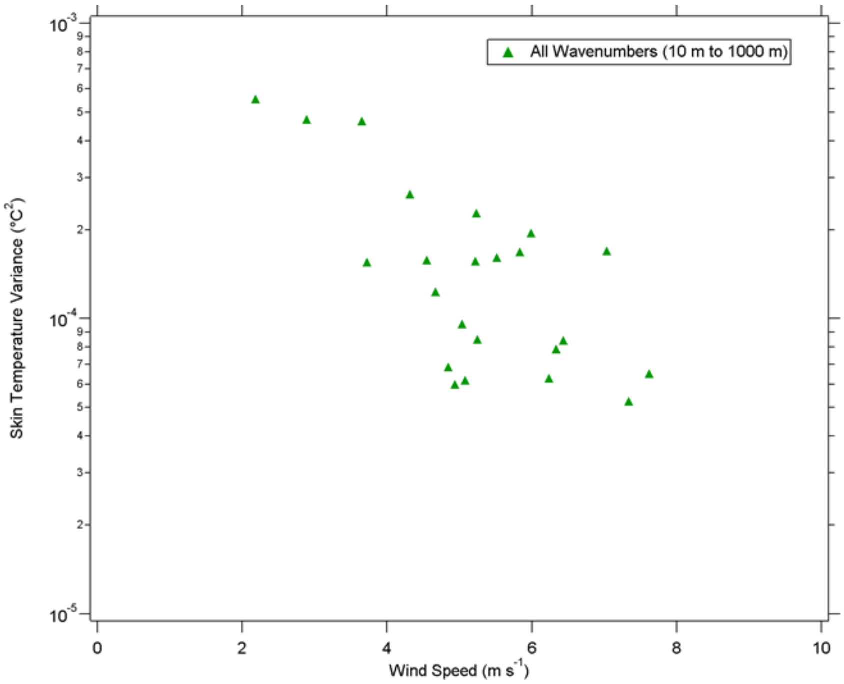



***Figure 5. (TOP) Spatial series of whitecap coverage (W%) measured from the NOAA P-3. (BOTTOM) Flight track for the NOAA P-3 color-coded to match the whitecap coverage.***

During onset equatorial convection of an MJO, strong winds were prevalent in a moist environment. Figure 4 shows a sequence of images of $SST_{skin}$ measured from the LDEO infrared camera along the flight track of the NOAA P-3 during our flights through a gust front on 22 November, 2011. The representative flight maneuver is described as a Radar Convective Element/Flux (RCE/FLX) Module and is shown. The sequence of images from top to bottom shows the $\mathrm{SST}_{\mathrm{skin}}$ along-track as the NOAA P-3 flew across the gust front from the convective side to the non-precipitating side. The evolution of the sea surface patchiness and upper ocean structure during convective events is demonstrated and representative of multiple instances that build up a consistent picture. Evidence suggests that the sea surface patchiness quickly evolves from its initial state to a system dominated by Langmuir circulation (LC) as the convective front (precipitation / high winds) propagates over a specific location, to a system behind the convective front ( no precipitation / winds??) where the sea surface patchiness appears without the strong forcing. Small-scale temperature variability of 0.2°C $\mathrm{m}^{-1}$ with horizontal patchiness scales of O(10-50) m. Small-scale temperature variability of 0.1°C $\mathrm{m}^{-1}$ with horizontal wind row / LC scales of O(10-50) m. Langmuir circulation organizes the fresh water and then sea surface patchiness evolves after the water slumps back. These features are related to both the fresh water lenses as well as sea surface patchiness. Goal is to measure the scales of coherent structure to compare with the MO Length scale.



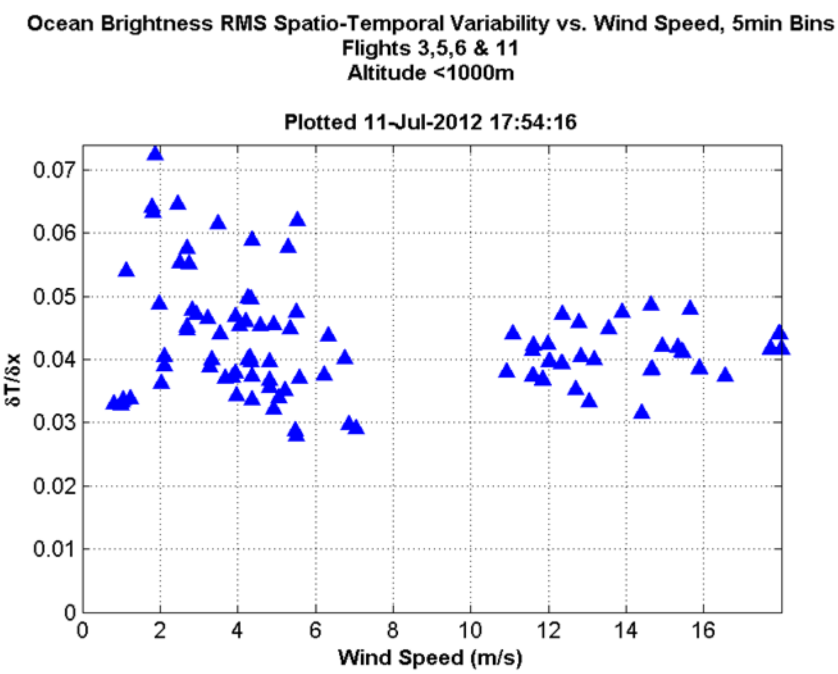




***Figure 6. (TOP) $SST_{skin}$ variability versus wind speed measured during CBLAST-Low. (BOTTOM) $SST_{skin}$ variability versus wind speed measured during DYNAMO.***

We have already discussed the evolution of the short fetch gravity wave field in Figure 1 using measurements from the Riegl altimeter on board the R/V Revelle. We also quantified the spatial structure of wave breaking through the convective events. We have multiple instances to build up consistent picture. Figure 5 shows a spatial series of whitecapping from the NOAA P-3 as it flew along and across a convective front. Evidence suggests that the wave breaking quickly develops across the convective front. No evidence to date of enhanced breaking ahead of the front. It is crucial to know the convective front orientation and propagation direction (S-POL, P-3 Radars, Revelle Radars) to extract the locations of breaking enhancement. Wave breaking is weak along the front yet enhanced behind. We are working to catalogue all convective RCE modules in terms of wave breaking (i.e., W%, $\Lambda(c)$).

During CBLAST-Low, we observed that the $SST_{skin}$ variability decreased with wind speed for low to moderate wind speeds as shown in Figure 6 (TOP). During DYNAMO, we observed the same trend in $SST_{skin}$ variability for low to moderate wind speeds as seen in Figure 6 (BOTTOM). However, at wind speeds greater than 10 m $s^{-1}$, the $SST_{skin}$ variability hits a plateau and remains constant. Precipitation at these higher wind speeds will add temperature variability as the cold rain is accumulated at the surface and mixed in the near-surface layer. As we have seen, at low wind speeds, the large-scale structure of freshwater cold pools on the water surface can extend kilometres as seen in Figure 3. However, at moderate to high wind speeds during active convection, we see a multitude of small-scale temperature structures of O(10-50m) related to upper-ocean processes as shown in Figure 4.

Convective clouds systems interact with the ocean surface and atmospheric boundary layer. Convective downdraft and fresh water pools from the rain induce a large spatial and temporal variability in the sea surface temperature (SST), which in turn affect the development of convective cloud systems and air-sea fluxes. Aircraft data are used to characterize the structure of convective cold pools and the surface/boundary recovery during the convectively suppressed and active phases of MJO. Shuyi Chen from RSMAS has studied the convective cloud system-induced cold pool duringn DYNAMO and its boundary layer recovery time using dropsonde data from AXBTs. She has suggested that $SST_{skin}$ variability is an important constraint on the determination of the recovery time of these atmospheric and oceanic cold-pool events. The structure observed in the variability of $SST_{skin}$ in Figure 6 (BOTTOM) is the same behavior observed for the recovery time of the cold pool suggesting that the recovery of the cold pool is very closely tied to the variability in $SST_{skin}$.

## IMPACT/APPLICATIONS

Understanding the complex processes involved in locations such as the MJO as it passes over the eastern Indian Ocean are necessary steps for evaluating the modulation of SST and atmosphere-ocean feedbacks, for validating ocean and climate models, and for making prognostic assessments of oceanic circulation.

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